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Fiber-Optic Hydrophone Arrays: Radial Temperature Compensation Package for Bragg Gratings

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PREFACE

This report was prepared under NUWC Division Newport Project No. 0602314N, "Thin Optical Towed Array," principal investigator Antonio L. Deus (Code 2141). The sponsoring activity is the Office of Naval Research (ONR-321SS, Donald Davidson).

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13. ABSTRACT (Maximum 200 words)

A new method of packaging fiber Bragg gratings to stabilize their wavelength over temperature variations has been demonstrated. This method uses a ceramic with a negative coefficient of thermal expansion to offset the fiber thermo-optic effect. A unique radial package compatible with fiber-optic hydrophones was demonstrated.

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FIBER-OPTIC HYDROPHONE ARRAYS: RADIAL TEMPERATURE COMPENSATION PACKAGE FOR BRAGG GRATINGS

1. INTRODUCTION

Fiber-optic sensor systems using reflective time division multiplexing (TDM) sensors have been presented by others.[1] These sensors use multiple partially reflective mirrors in a single fiber, which eliminates the couplers common to most forms of fiber sensor arrays and thus greatly simplifies the array fabrication. Replacement of the broadband partial mirrors in Dakin et al.[1] with Bragg gratings, and the use of grating pairs or groups at multiple wavelengths, allows a greater number of sensors per fiber and reduces array crosstalk.

Hydrophone sensors of this type have been constructed with the form shown in figure 1. A pair of fiber gratings at matching wavelength and a fiber span between them form the sensor interferometer. The fiber is wrapped radially around an air-filled cylindrical mandrel. Acoustic pressure compresses the mandrel and changes the length of the fiber, resulting in a phase change detected by the interferometer. In a large linear hydrophone array, one hydrophone may be connected to the next by a flexible interlink. A fiber containing multiple sets of Bragg gratings and sensor spans can then be wound to form one hydrophone, wound across an interlink to the next hydrophone, wound to form the next hydrophone, and so forth. In this way, large linear hydrophone arrays can be constructed in an automated, low-cost manner.

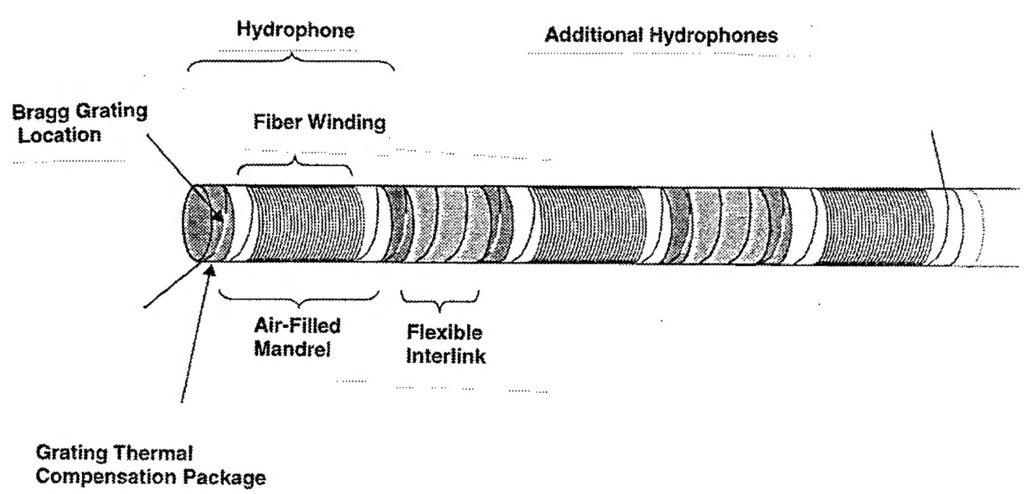

Figure 1. Hydrophone Array Construction with Radial Grating Temperature Compensation Package

The objective is to multiplex a large number of sensors using wavelength division multiplexing (WDM). This requires relatively narrow bandwidth Bragg gratings. It is necessary for the narrow line-width interrogation laser to remain aligned to both gratings, despite temperature changes that can shift the response of the Bragg gratings. A temperature compensation package that is compatible with the radial winding of the sensor fiber is required for the gratings.

A radial temperature compensation package for Bragg gratings is developed. It makes use of a unique ceramic with a negative coefficient of thermal expansion to offset the thermo-optic coefficient of the fiber Bragg grating. The principle is equally applicable to other nonradial geometries.

2. DEVICE DESCRIPTION

Fiber Bragg gratings experience a shift of their reflection wavelength with temperature, given by

$$\delta\lambda/\lambda = (\alpha + \xi)\Delta T \,, \tag{1}$$

where ΔT is the temperature change, α is the thermal coefficient of expansion of the fiber, and ξ is the thermo-optic coefficient. Coefficients for silica fiber are 0.55×10^{-6} °C^{-1} and 8.31×10^{-6} °C^{-1}, respectively. The total is dominated by the thermo-optic coefficient and results in a shift of 0.7 nm for a Bragg grating at 1550 nm and a 50° temperature shift. This shift is significant compared to the standardized 0.8-nm dense WDM channel spacings.

The temperature compensating grating package is shown in figure 1. A cylindrical body of zirconium tungstate[2] ceramic is designed to mount on the end of the sensor with an outer diameter to allow the sensor fiber to be wound directly from the sensor mandrel onto the ceramic grating mount. The fiber is wound onto the grating mount under tension and attached to the mount with a cover layer of epoxy. The zirconium tungstate has a negative coefficient of thermal expansion, which offsets the thermo-optic coefficient of the fiber. As the temperature rises, the refractive index of the grating increases, shifting the reflection wavelength to a longer wavelength. The grating mount shrinks, however, relieving some of the tension on the grating and shifting it to a shorter wavelength. The two effects offset each other to reduce the thermal shift of the grating.

3. FABRICATION

Zirconium tungstate (ZrW_2O_8) is a complex oxide that exists as three polymorphs, the properties of which are summarized in table 1.

The alpha form of ZrW_2O_8 has cubic symmetry and is stable in the temperature range of -270°C to 155°C. At 155°C it undergoes a second-order phase transition to a disordered phase known as the beta polymorph. This is accompanied by a decrease in its coefficient of thermal expansion (CTE) by almost a factor of 2. If the temperature of ZrW_2O_8 exceeds 780°C, decomposition occurs, and the resulting CTE of the products is positive. When α- ZrW_2O_8 is subjected to pressures greater than 30,000 psi at room temperature, it transforms to the gamma polymorph with orthorhombic symmetry, which readily reverts back to the alpha form upon heating above 120°C.

Table 1. Zirconium Tungstate Polymorph Properties

Polymorph	Crystal Symmetry	CTE (10^{-6}/°C)	Transition Temperature (°C)
Alpha	Cubic	-8.8	155 (conversion to beta)
Beta	Cubic	-4.9	780 (decomposition)
Gamma*	Orthorhombic	a: -1.88 b: -0.68 c: -0.92	120 (reversion to alpha)

*High pressure form

ZrW_2O_8 was obtained as a polycrystalline powder from Wah Chang, Inc. The powder was analyzed for phase composition by x-ray diffraction with a Siemens 5000 diffractometer. Decomposition temperature was confirmed by thermogravimetric analysis using a Du Pont thermogravimetric analyzer, Model Hi-Res TGA 2950. Duramax B-1031, a polyacrylate, was obtained from the Rohm and Haas Company and used as a binder in the sintering experiments.

Unlike most ceramic oxides, ZrW_2O_8 cannot be sintered to the density and hardness that is usually required for ceramic applications because it has a relatively low decomposition temperature of 780°C. Traditionally, organic binders have been used to aid in the sintering of ceramics, but only at high calcination temperatures—usually exceeding 1000°C. In the case of ZrW_2O_8, the addition of a binder followed by calcination at 750°C (limited by the decomposition temperature) did not result in a material with sufficient mechanical strength. To circumvent this problem a new approach was tried, which involved addition of a binder with subsequent heat treatment at low temperature.

A cylindrical pellet (19-mm diameter by 6-mm thickness) was prepared from a mixture of ZrW_2O_8, Duramax B-1031, and distilled water. Approximately 7.0 grams of ZrW_2O_8 and 0.35 gram of binder were ground together using a mortar and pestle. When the mixture was thoroughly homogenized, 0.5 gram of water was added, and all contents were ground together. The mixture, which had a paste-like consistency, was transferred to a cylindrical uniaxial die, and the die was mounted in a laboratory press. The mixture was pressed at 23,000 psi for 30 seconds. The pellet was then removed from the die and placed in a 200°C drying oven for 3 hours. The resulting pellet was dark brown in color and appeared to have good chip resistance and hardness. Because of the low processing temperature, most of the binder remained in the ceramic; however, it should have little effect on the CTE because only a small amount is present. Furthermore, the binder should remain stable over the usable temperature range of the device, which will not exceed 200°C.

The coefficient of thermal expansion was determined using a Du Pont thermo-mechanical analyzer, Model TMA 2840. Figure 2 shows a plot of linear expansion versus temperature for ZrW_2O_8 with polymer binder added. As expected, there is a noticeable inflection at approximately 155°C that can be attributed to the alpha to beta polymorph transition. The CTE was calculated from the slope in the region from 150°C to 200°C and was found to be -7.8 10^{-6}/°C. The presence of polymer caused the magnitude of the CTE of ZrW_2O_8 to decrease slightly from its literature value of -8.8 10^{-6}/°C.

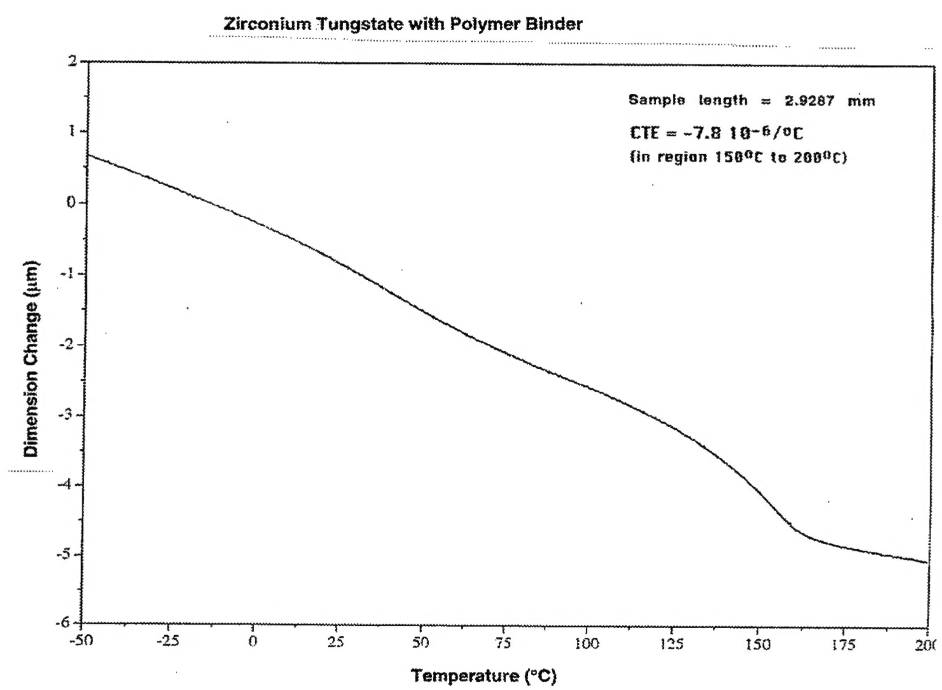

Figure 2. Thermal Expansion of Zirconium Tungstate with a Polymer Binder

The cylindrical ceramic sample was wound with an optical fiber containing a Bragg grating. The winding tension was sufficient to shift the grating reflection peak wavelength by 1.6 nm. The grating was bonded to the mount with an ultraviolet-cured cement.

4. RESULTS

The wavelength shift of the Bragg grating and temperature compensation package was measured. The spontaneous emission from an Erbium-doped fiber amplifier (EDFA) illuminated the grating through a fiber coupler. The reflected signal was measured by an optical spectrum analyzer. The package temperature was varied, and the peak wavelength of the grating reflection was recorded. Figure 3 shows the variation with temperature of an unmounted grating and the temperature-compensated grating. The temperature sensitivity of the grating has been significantly reduced. The 0.1-nm variation exhibited between 0°C and 50°C is sufficient for a dense WDM system operating at the ITU 100-GHz grid. The slight decrease in wavelength at higher temperature suggests that the package is overcompensating for the thermo-optic effect. This being the case, it should be possible to tailor the material properties for further reduction in the temperature variability. By processing ZrW_2O_8 with compounds that possess a positive CTE (such as aluminum oxide), the overall CTE of the mixture could be adjusted to a value less than that of ZrW_2O_8 by itself.

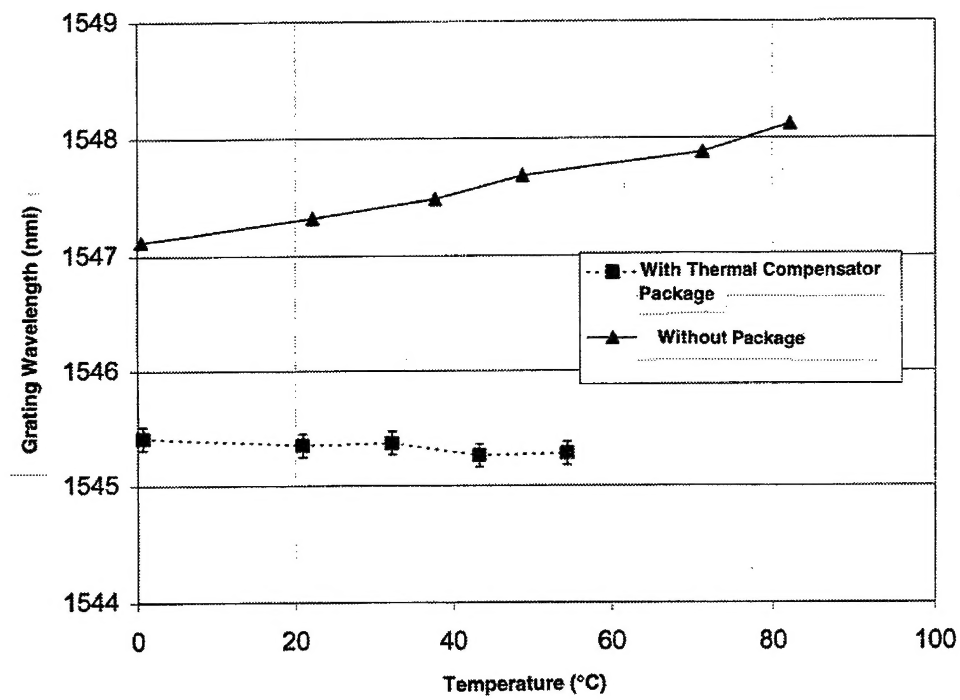

Figure 3. Bragg Grating Reflection Versus Temperature for the Grating Mounted on the Temperature Compensating Package

5. CONCLUSIONS

A Bragg grating temperature compensation package based on a unique ceramic material has been demonstrated. The package eliminates the normal shift of Bragg grating wavelength with temperature. The cylindrical package has radial wrapping of the fiber and is compatible with the construction of fiber-mandrel-based hydrophones. The principle of operation is not limited to this geometry and is applicable to typical linear grating packages.

6. REFERENCES

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